Fast mixing using the Shear Superposition Micromixer

F.Bottausci, C. Cardonne, I. Mezič and C. Meinhart

University of California Santa Barbara

Abstract

We are presenting experimental studies and numerical simulations to analyze an actively controlled mixer. The current design of the micromixer is called "shear superposition micromixer". This micromixer consists of a main mixing channel where unmixed fluids are perturbed by jet flows emanating from series of transverse channels. Mixing of two fluids is achieved using the kinetic of the side jet flows. We quantify, numerically and experimentally, the degree of mixing achieved using the Mixing Variance Coefficient (MVC). We present some flow properties. Single channel mixing can be very good when amplitude and frequency are chosen carefully.

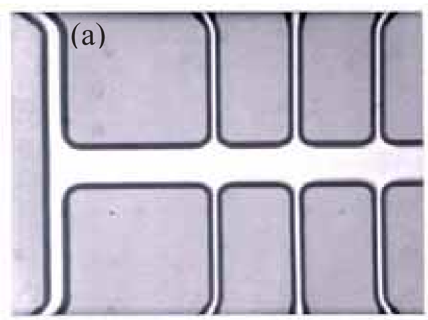
Introduction

Mixing time of two fluids can be enhanced when the interface area between the fluids is increased by stretching and folding, so that diffusion between the fluids has to occur over a relatively small distance. At the microscale, the Reynolds number Re = UL/ν, where U is the characteristic velocity, L the characteristic lengthscale and ν the kinematic viscosity, is close to unity or smaller. The flow cannot be turbulent. A solution to enhance the mixing is to create a chaotic advection [1, 2] based strategy which has the advantage of producing an exponential rate of mixing, as opposed to an algebraic rate (e.g. t^{-1}), which is achieved e.g. by inducing vertical motion. Thus advective stretching and folding is still desirable in order to improve the effective diffusion coefficient.

The microscale mixers can be divided in two broad classifications: the active and the passive micromixers. If there are no moving parts used to produce the mixing, the mixer is defined as passive micromixer [3, 4, 5]. These passive designs are such that the flow in the channel is fully three-dimensional, which is a necessary condition for a laminar steady flow to have chaotic trajectories. The first active micromixer developed by [6] is based on chaotic advection resulting from a source/sink system, where unmixed fluids are pumped into a mixing chamber, and then two source/sink systems are alternately pulsing the flow.

Micromixer Design

The current design of the micromixer, called "shear superposition micromixer", was developed at UCSB in 1998 [7]. This is a continuous through-flow micromixer consisting of a main channel with three cross-flow side channels that are capable of producing time-dependent shear flow in the direction transverse to the main stream. The micromixer design is shown in Figure 1. The micromixer is a silicon-etched device where the main channel is 2h wide, 13h long and h deep (h = 100 microns). The secondary channels are 5h long and h/2 wide.



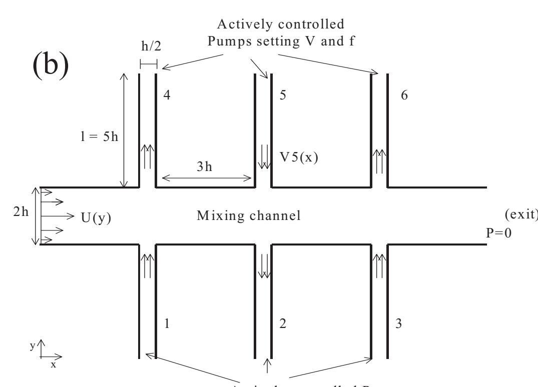


Figure 1. (a) micrograph of the mixing chip, (b) schematic showing one possible flow configuration.

NSTI-Nanotech 2005, www.nsti.org, ISBN 0-9767985-0-6 Vol. 1, 2005

Flow in the main channel is manipulated by controlling time-dependent oscillating flow from three pairs of secondary channels. The secondary channels induce time-dependent cross-stream momentum on the main channel flow which affects the fluid motion. Each side channels pair is controlled independently. The parameters (flow rate, frequency, and amplitude of oscillations) are accurately controlled using *LABview*.

Figure 1a shows a top view of the experimental chip and a description of the fluid motion into the mixer is shown in Figure 1b. A 3-D Poiseuille profile is specified at the entrance of the main channel, which is eventually perturbed by the secondary channels. The pressure at the entrances of the secondary channels, far from the main channel, is specified to be sinusoidal in time, with each pair having independent frequencies. The numerical simulations are performed with the commercial CFD software FLUENT.

Mixing Variance Coefficient

To quantify the degree of mixing, numerically and experimentally, we use the *Mixing Variance Coefficient* (MVC).

We use the so-called mixing variance coefficient (MVC) function to quantify a homogenous particles distribution of the two fluids initially unmixed at different scales.

The MVC is defined as follows $MVC = \frac{1}{S^2}\sum_{1}^{S^2}\left(\rho_k - 0.5\right)^2$ where ρ_k is the average particle label in the box k and S defines the size at which we look at the mixing.

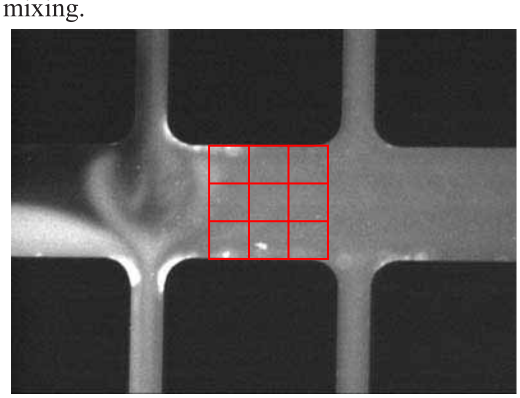


Figure 2: Example of scheme used to compute the MVC. At the entrance of the main channel, the water appears dark and the dye white. Here S=3.

The best mixing is achieved when the mixing variance coefficient is equal to zero. When MVC = 0.25, there is no mixing. The MVC definition can be extended to the experimental measurements. In this case, the mixing is analyzed by taking pictures of the channel through a microscope (figure 2). In this paper, the MVC is calculated in the x-y plane at the middle of the channel (z=50microns).

Results

The effectiveness of the mixer is evaluated exploring several different flow configurations by varying the frequencies, the amplitude of oscillation within the secondary channels and the flow rate in the main channel.

Optimization for one side channel oscillating

We present an optimization of the mixing for the parameters mentioned above. Figure 2 is a snapshot of the flow behavior when one side channel is activated. Before the intersection, the water appears dark and the dye solution white. The flow is coming from the left. The distance between the channel entrance and the intersection is 650microns. The fluids used are dionized water and an aqueous solution of fluorescent particles of 98nm in diameter. The diffusivity of the solution calculated using the Stokes – Einstein formula is 2.2 $\mu m^2/s$. The length over each fluid has diffused before the intersection is 0.1 micron.

The mean velocity, measured using micro–PIV technique is 1.3cm/s in the main channel for a flow rate of 277 pl/s. The Reynolds number associated is $Re \approx 3$.

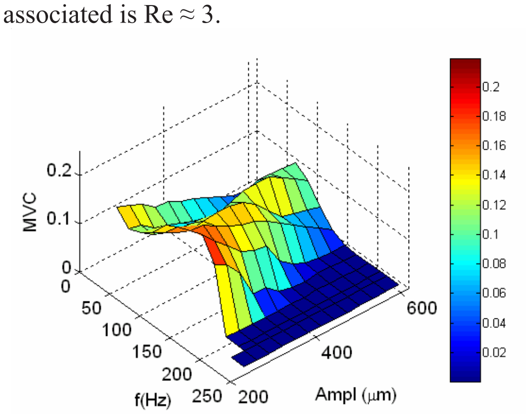


Figure 3: Mixing Variance Coefficient function for different amplitudes and frequencies. The flow rate in the main channel is 1ml/h.

Figure 3 shows the optimization of the mixing for the parameters amplitude and frequency of oscillations applied to the side channel. The measurements have been made 400 microns downstream the intersection. S is fixed at 70 meaning the MVC is computed at the scale 2.5 microns. Three regions appear. A central band of poor mixing where the MVC reaches 0.18. Decreasing the frequency, the mixing becomes better and the curve forms a valley. At high frequency, the curve forms a plateau where the MVC is lower than 0.01. This is a region of complete mixing. The Reynolds number associated with the side channel in this region is between 12 and 50. In this region, the range frequency/amplitude induces the flow emanating from the side to create two recirculation regions at the intersection main channel/side channel every half a period. The effect is to produce multiple layers of fluids thus increasing the mixing. Another effect of the recirculations is to create particle motion in z-direction.
For high frequency and amplitude, it takes 10ms to completely mix the fluids over a distance of 200microns which is the distance to cross the intersection.

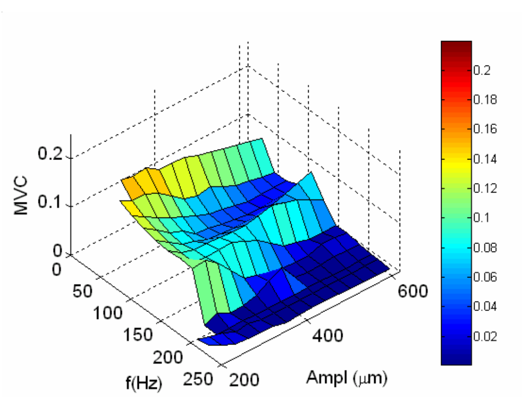


Figure 4: Mixing Variance Coefficient function for different amplitudes and frequencies. The flow rate in the main channel is 1.8ml/h.

Figure 4 shows the optimization for a higher flow rate in the main channel. The Reynolds number is Re ≈ 5.5. There are two bands of poor mixing emerging but for high frequency and amplitude the MVC is still lower then 0.01. Increasing Re associated with the main channel globally enhances the mixing. This can be explained from the Taylor dispersion point of view. The convection is more important, stretching the fluids layers reducing the time needed to diffuse through the fluid layers.

Application to biological fluids

The mixing process can be applied at different biological samples as DNA, cells or viruses. Figure 5 shows the results of two numerical simulations using the commercial CFD software Fluent. It is a comparison of the mixing between two aqueous fluids (viscosity $1\text{mm}^2/\text{s}$) and two fluids more viscous ($3.95\text{mm}^2/\text{s}$) that are close to the blood even if they are Newtonian. The diffusivity is fixed at 10^{-9} m^2/s. The frequency and amplitude used are 220Hz and 500 microns respectively. The mixing for the water is 4 times better for a spatial scale of 18 microns which is the ratio of the viscosities.

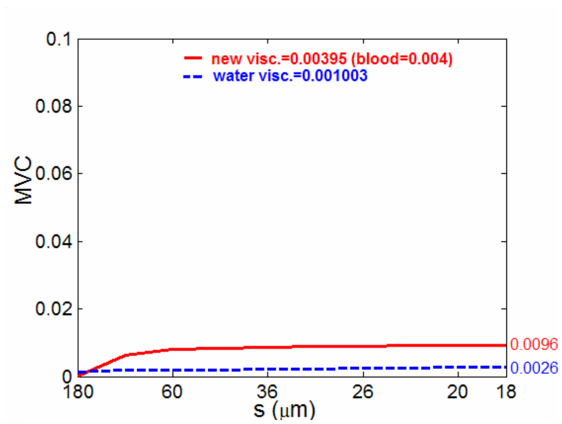


Figure 5: Comparison of the MVC for two different viscosities. The flow rate in the main channel is 1ml/h.

Conclusion

The results presented here correspond to an analysis of the mass transport in an active micromixer. Optimization of the mixing using the MVC function for one pair of side channels activated show a fast and robust mixing for high amplitude and frequency oscillations. Fluids can be mixed in 10ms over a length of 200microns. Numerical simulations of mixing for fluids having viscosity properties close to the blood show a mixing inversely proportional to the viscosity. More experiments will be performed using DNA samples.

1. H. Aref. Stirring by chaotic advection. Journal of Fluid Mechanics, 143:1–21, 1984.

2. J.M. Ottino. The Kinematics of Mixing: Stretching, Chaos and Transport. Cambridge University Press, Cambridge, 1989.

3. R. Myake, T.S.J Lammerink., M. Elwenspoek and J.H.J. Fluitman. Micro Mixer with fast diffusion. In *Proceeding of the IEEE Micro Electro Mechanical Workshop*, Fort Lauderale, FL 1993 pages 248-253

4. H. Song, J.D. Tice and R.F. Ismagilov, A Microfluidic System for Controlling Reaction Networks in Time Angew. In *Chem. Int. Ed 2003*, 42 No 7.

5. A. D. Stroock, , S. K. W. Dertinger, , A. Ajdari, I. Mezic, H. A. Stone, & G. M. Whitesides, 2002 Chaotic mixer for microchannels. *Science* **295**, 647–651.

6. J. Evans, D. Liepmannand, A.P. Pisano. Planar laminar mixer. In 10th Annual Workshop of Micro Electro Mechanical System, Nagoya, Japan, pp.96-101 1997.

7. M. Volpert, I. Mezic, C. D. Meinhart, and M. Dahleh. An actively controlled micromixer. pages 483–487. Proceedings of the ASME Mechanical Engineering International Congress and Exposition, MEMS, Nashville, TN 1999.